The Development of Technologies for Small Systems of Highly-efficient Natural Gas Cogeneration

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1. Introduction

A report from the General Group and Supply-Demand Group of the Advisory Committee on Energy and Natural Resources (July, 2001) has set the goal of expanding the capacity of natural gas cogeneration systems to 4.64 million kilowatts by fiscal 2010 (excluding the capacity from steam turbine type cogeneration systems). With the Kyoto Protocol, Japan has set the goal of 4.98 million kilowatts. The present situation concerning the spread of natural gas cogeneration systems, as shown in Figure 1, is characterized by a higher penetration into the industrial and other sectors that have a relatively high heat demand and a lower penetration into the commercial and public welfare sector with the exception of a few types of businesses. This is due to the fact that even though the commercial and public welfare sector carries a potentially large demand for natural gas cogeneration systems, the level of heat demand at individual installations is low, and therefore, a small natural gas cogeneration system of today, which is inefficient in electric power generation, will not offer many advantages in terms of economy and energy conservation. To ensure we arrive at the aforementioned goals concerning the wider use of natural gas cogeneration systems, it is critical we develop a small and efficient gas engine in the near future.

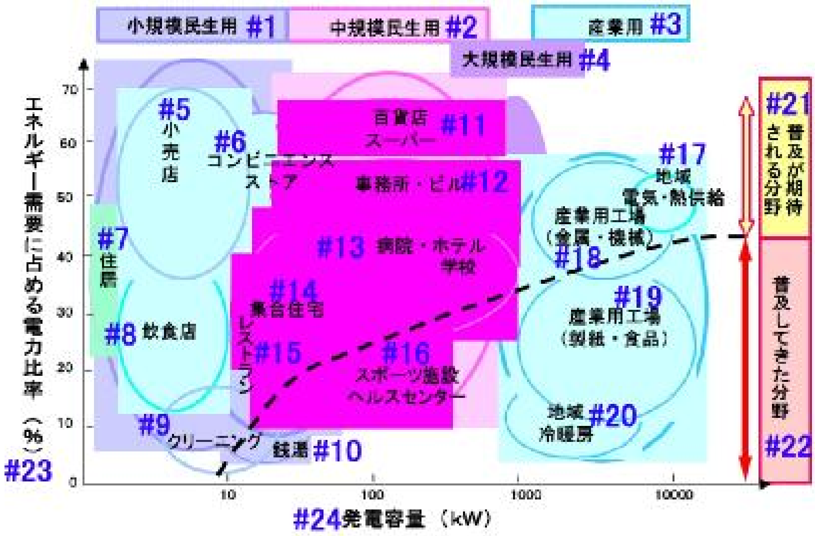
To develop a highly-efficient small gas engine using homogenous-charge compression ignition (HCCI) technology – a new ignition technology characterized by high efficiency and low NOx emissions – the Japan Gas Association (JGA) and Yanmar Co., Ltd. (YMR) were jointly engaged in a research project with the New Energy and Industrial Technology Development Organization (NEDO) known as the “Development of Technologies for Small Systems of Highly-efficient Natural Gas Cogeneration.” This project began in October of 2003 and ended at the end of March, 2006 as originally planned, after surpassing our initial performance goals set for the combustion process. (The project period was two and a half years.)

This paper briefly describes the project and reports on its achievements.

2. Organizational Arrangements and Targets for the Development Activities

JGA mainly took responsibility for the optimization of engine specifications and the development of a small, efficient turbocharger; YMR took responsibility for the development of the engine system, including the development of a multi-cylinder engine and combustion control techniques. JGA improved the efficiency of development activities by establishing a project promotion team and satellite offices at Tokyo Gas Co., Ltd., Osaka Gas Co., Ltd. and Toho Gas Co., Ltd.

Our aim was to achieve the following with the engine we developed: 20kW class electric output, engine thermal efficiency of 38% or higher (LHV based), and the NOx emission level of 100ppm or less (oxygen 0% equivalent value).



#1 Small-scale commercial and public welfare applications

#2 Mid-scale commercial and public welfare applications

#3 Industrial applications

#4 Large-scale commercial and public welfare applications

#5 Retail stores

#6 Convenience stores

#7 Residence

#8 Eating establishments

#9 Laundry service

#10 Public baths

#11 Department stores / Supermarkets

#12 Offices and large buildings

#13 Hospitals, hotels and schools

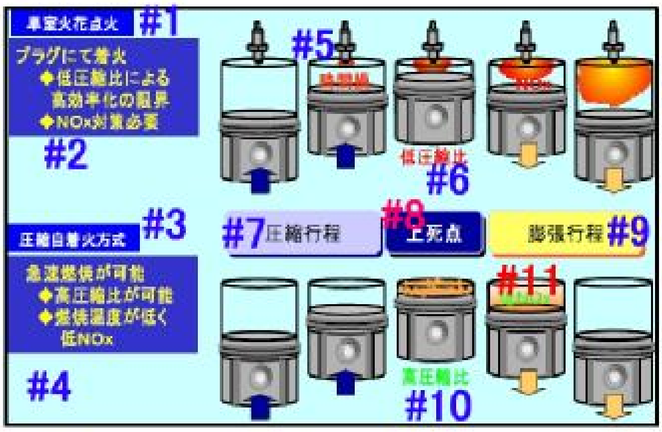
#14 Flats and condominiums

#15 Restaurants
#16 Sport facilities and health resort facilities
#17 District power/heat generation
#18 Industrial factories (metal/machinery)
#19 Industrial factories (paper manufacturing and food)
#20 District space cooling/heating
#21 Areas for further penetration in future
#22 Areas into which penetration has been made
#23 Share of electricity in the energy demand (%)
#24 Electric power generation capacity (kW)

Figure 1 Penetrations of natural gas cogeneration into various areas

3. HCCI Engine

Research and development activities were conducted on the subject of the HCCI technology, a technology expected to decrease NOx emissions from a diesel engine and improve the efficiency of a gasoline engine in the low load range. Figure 2 illustrates the features of an HCCI engine. An HCCI engine achieves combustion by auto-ignition: by means of adiabatic compression the premixed gas is brought to a bulk temperature high enough for it to automatically ignite. This allows a high compression ratio and a lean combustion free from constraints from the flame propagation range, thereby simultaneously achieving the two goals of high efficiency and low NOx emissions. However, it has been pointed out that such combustion cannot continue except in a narrow operating range, due to misfire and the problem of knocking. Figure 3 shows the thermal efficiency of the test unit of a single-cylinder natural gas engine running with HCCI combustion, without supercharging, at a engine speed of 1200rpm and compression ratio of 17:1. As shown, the output range in which the engine can operate changes with the intake temperature (T_{in}); lowering the value of T_{in} improves the output and thermal efficiency. On the other hand, the operation range is significantly narrowed at the point of maximum efficiency due to knocking and misfire. Nevertheless, an engine used in a cogeneration system does not have to be run in a wide load range because the operating load is relatively constant. An engine based on the principle of auto-ignition by compression, therefore, is expected to be suitable for a cogeneration system.



#1 Open chamber with spark ignition

#2 Ignition by a spark plug:

- Efficiency restricted by the low compression ratio.
- Requires a measure for reducing NOx emissions.

#3 Auto-ignition by compression

#4 Enables fast combustion:

- Allows a high compression ratio.
- Achieves a low combustion temperature and low NOx emissions.

#5 Time loss

#6 Low compression ratio

#7 Compression stroke

#8 Top dead center

#9 Expansion stroke

#10 High compression ratio

#11 Low NOx

Figure 2 Comparison between spark-ignited engine and HCCI engine

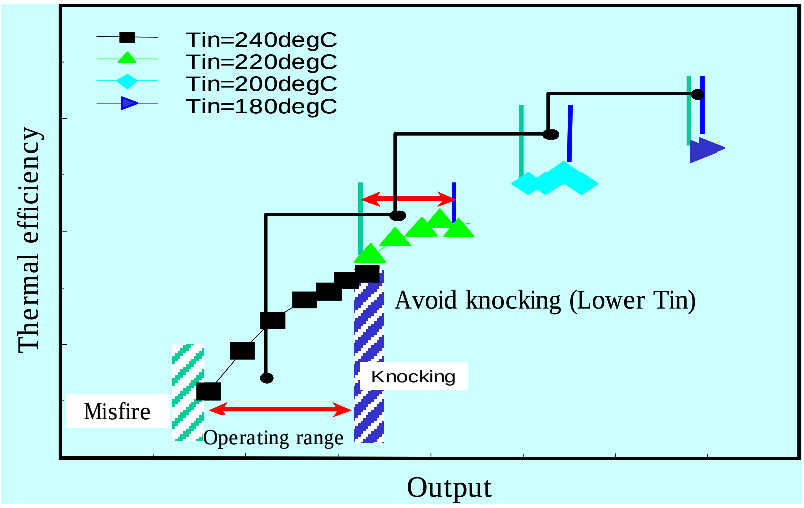


Figure 3 Engine output and efficiency

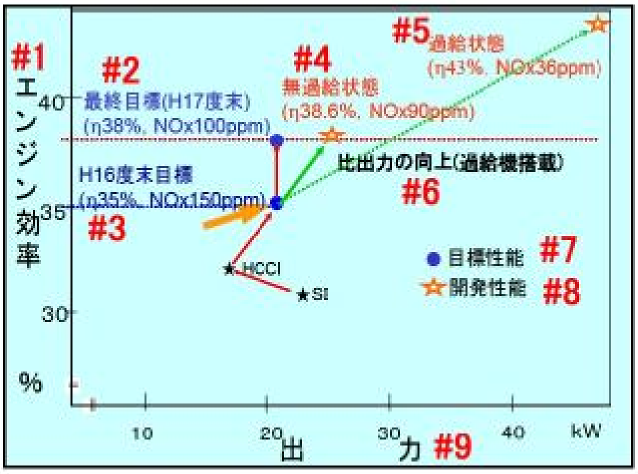
In addition to the optimization of engine specifications, the practical application of the HCCI engine requires the following: the development of combustion control techniques on account of the ignition timing, the duration of combustion, and so on; the development of the start-up method; the development of technologies for improving the specific power.

4. Achievements

Figure 4 shows the development roadmap. Table 1 lists the specification of the HCCI engine we developed. We started development activity by collecting data on an existing spark-ignited engine, and in a subsequent stage of development, we converted this engine into an HCCI engine. Our achievements include the following:

a) At the end of fiscal 2005, we achieved the final target with a natural aspiration HCCI engine system;
b) We successfully developed a small turbocharger, which demonstrated the overall efficiency of the world's highest level;
c) We installed the turbocharger to the HCCI engine and confirmed the engine had the potential of the world's highest level.

The following subsections outline the project with a focus on JGA's achievements.



#1 Engine efficiency (%)

#2 Final target (achieved at the end of fiscal 2005)

#3 Target for the end of fiscal 2004

#4 Without supercharging

#5 With supercharging

#6 Improvement of the specific power (with the turbocharger)
#7 Target performance
#8 Achieved performance
#9 Output

Figure 4 Development roadmap

Table 1 Specifications of the developed engine

Item	Spark ignition	NA HCCI	TC HCCI
Bore	98mm	←	←
Stroke	110mm	←	←
Number of cylinders	4	←	←
Displacement	3300cc	←	←
Revolution speed	1900min-1	1700min-1	1800min-1
BMEP	0.43MPa	0.52MPa	0.92MPa
Compression ratio	9	25.9	21
Ignition	Spark	HCCI	←
Intake temperature	Room temperature	Approx. 60℃ (with heat exchanger)	Approx. 80℃ (with intercooler)

NA: natural aspiration; TC: supercharging with a turbocharger

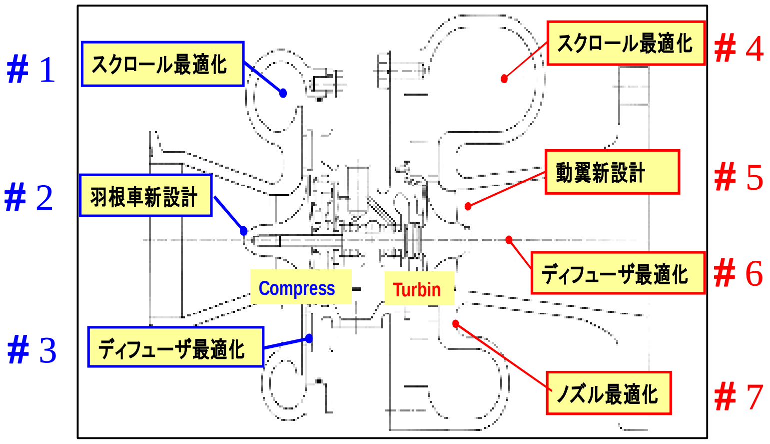
4-1 Achieving the Target with Normal Aspiration

Using the outcomes of the tests and analyses of a single cylinder engine conducted by JGA, YMR designed and fabricated a multiple cylinder engine. The research and development activities brought about: (1) an understanding about the basic performance of the multi-cylinder engine and (2) the establishment of a control scheme that allowed stable operation under the rated conditions. Thus, with the natural aspiration engine, we recorded performance levels that exceeded our target: an output of 25kW; an engine thermal efficiency of 38.6% (LHV based; the target was 38%); and the NOx concentration of 90ppm in the exhaust (O_2 = 0% equivalent value; the target was 100ppm or less).

4-2 Development of a Highly-efficient Small Turbocharger

We developed a highly-efficient small turbocharger to improve the specific power of the engine. With this turbocharger, we successfully recorded the total efficiency of

65.6%, which is the highest in the world for a turbocharger of this class. Figure 5 outlines the points we emphasized during the development:



#1 Optimization of the scroll
#2 New design of the rotor
#3 Optimization of the diffuser
#4 Optimization of the scroll
#5 Optimization of the rotor blade
#6 Optimization of the diffuser
#7 Optimization of the nozzle

Figure 5 Points emphasized in the development of the turbocharger

4-3 Performance of the HCCI Engine with the Turbocharger

We installed the developed turbocharger to the multi-cylinder HCCI engine and evaluated its potential. The engine recorded the world’s highest potential for an engine of this class with an output of 49kW, an engine thermal efficiency of 43% (LHV based), with a concentration of NOx of 36ppm in the exhaust (O_2 = 0% equivalent value).

4-4 Research and Development for Practical Application

Using a single cylinder engine, we conducted a test to see how the HCCI engine performance may be affected if the constitution of the fuel gas (city gas, 13A) was changed, with the calorific value varying in the range from 44 to 46 MJ/Nm^3. The result has shown that engine performance is affected little by the constitution of the gas. Indeed, the engine can maintain the rated performance with a varied calorific value by changing the intake temperature by about 10°C.

5. Challenges toward Practical Application

Before a cogeneration system with an HCCI engine can be put to practical use, we believe the issues listed below must be overcome. YMR is planning to put the system to practical use after two years of research.

a) Establishment of the engine speed governing technology
b) Establishment of the start-up method
c) Establishment of the load connection/disconnection method (a faster method)
d) Reduction of the manufacturing cost
e) Ensuring durability

6. Acknowledgement

The technological development project reported herein, which was initiated as a joint research project with NEDO, ended successfully in March, 2006 after successfully attaining the goals set at the beginning. We acknowledge our gratitude to the members of the Special Committee for the Development of Highly-efficient Cogeneration Systems who provided us with precious inputs and guidance, and to our joint researchers at Yanmar Co., Ltd. who supported us in many ways.

Source: “City Gas Symposium” handouts